

## SECTION II.—GENERAL METEOROLOGY.

## TROPICAL RAINS—THEIR DURATION, FREQUENCY, AND INTENSITY.

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[Dated: Weather Bureau, Baltimore, Md., Jan. 3, 1916.]

The aim of the following discussion is to determine, by accurate measurements and calculations, the duration, frequency, and intensity of tropical rains and to compare the results obtained with similar measurements made in the middle latitudes.

For this purpose a representative area within each of the zones was selected in which accurate and detailed observations are available for a period sufficiently long to establish reliable normal values. The Tropics are represented by the island of Porto Rico, in the West Indies, and the Temperate Zone by the State of Maryland.

Attention is also directed to the influence of topography on the distribution and character of the rainfall in Porto Rico, and to the relation of the rainfall to the principal commercial crops, namely, sugar cane, coffee, tobacco, citrus fruits, and pineapples.

## A. DURATION OF RAINS.

Tropical rains are of short duration, compared with the rains of middle latitudes, owing to the greater freedom from cyclonic storms in the Tropics. The duration of rains at San Juan is less than an hour, while at Baltimore, Md., it is about eight hours. The tropical rains are of fairly uniform duration in all months, while in the high latitudes the winter rains last decidedly longer than those of the summer months. At Baltimore rains of the colder half year continue about 10 hours and those of the warmer months less than 4. The explanation of this difference in duration is found in the greater frequency of the cyclonic storms of the winter season.\* The rains of the Tropics closely resemble the summer rains of the middle latitudes during a spell of unsettled weather. (Table 1 and fig. 1.)

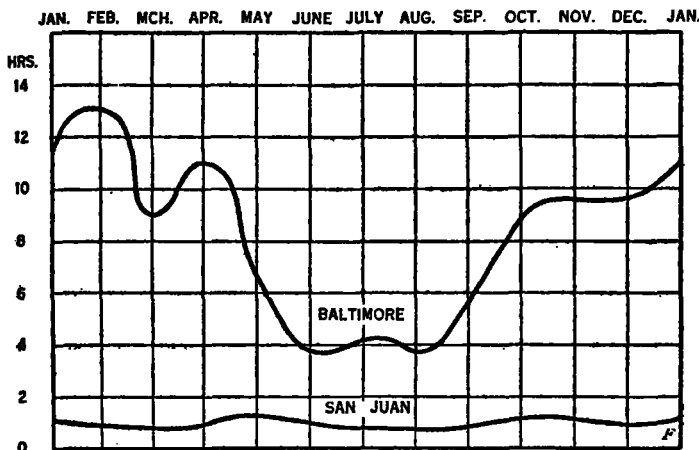


FIG. 1.—Average duration of rains (hours and minutes) at Baltimore, Md., and San Juan, P. R.

TABLE 1.—Duration of rainfall (in hours and minutes).

	Jan.	Feb.	Mar.	Apr.	May.	June.	July.	Aug.	Sept.	Oct.	Nov.	Dec.	Year.	No. of rains.
San Juan (average 3 years).....	0:59	0:40	0:50	0:54	1:12	0:52	0:54	0:52	0:57	1:05	0:54	0:43	0:53	1,538
Baltimore (average 10 years).....	11:10	13:10	8:45	11:00	7:00	3:30	4:00	3:30	5:15	8:05	9:25	9:20	7:50	3,000
San Juan (dry year, 1907).....	0:38	0:39	0:28	0:40	0:54	0:48	0:31	0:34	0:26	0:49	0:36	0:31	0:36	597
San Juan (wet year 1910).....	0:58	0:46	1:03	1:23	1:07	0:44	0:38	1:01	1:29	0:51	1:02	1:21	1:01	460

The duration and character of rains is shown in an unusual manner by the use of what may be termed "rain autographs." These are automatic records made by the rain drops falling upon specially prepared sheets of paper covering a revolving drum, the drum being under cover, with the exception of a small aperture in the top of the cover.

\* The records show not only the time of beginnings and endings of the lightest rains, but their frequency and, in a rough way, their intensity. (Fig. 2A and 2B.)

## Duration of excessive rains.

On comparing what are officially designated as excessive rains,<sup>1</sup> it is found that their duration is greater in the Tropics than in the higher latitudes. This is shown by comparing, for instance, the average duration of excessive rains at San Juan, P. R., and at Baltimore, Md. The comparison covers a period of 10 years (1894 to 1903) at Baltimore, and of 12 years (1899 to 1910) at San Juan, and includes all of the rains of the respective periods classed as excessive by the Weather Bureau. The average duration of excessive rains at San Juan is 35 minutes, and at Baltimore 20 minutes (Tables 2 and 3).

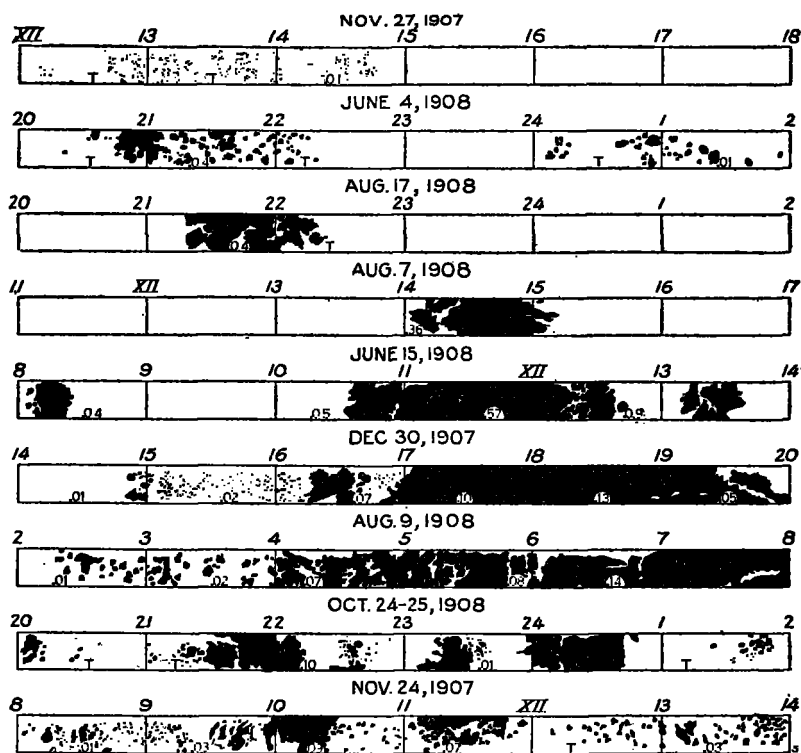
TABLE 2.—Average duration of excessive rains (in minutes).

	Jan.	Feb.	Mar.	Apr.	May.	June.	July.	Aug.	Sept.	Oct.	Nov.	Dec.	Year.	Cases.
San Juan, P. R. (12 years).....	39	20	37	59	43	19	28	26	35	31	34	45	35	193
Baltimore, Md. (10 years).....	22	.....	6	19	18	21	24	22	26	.....	.....	20	20	78

## Limits at which precipitation may be considered excessive.

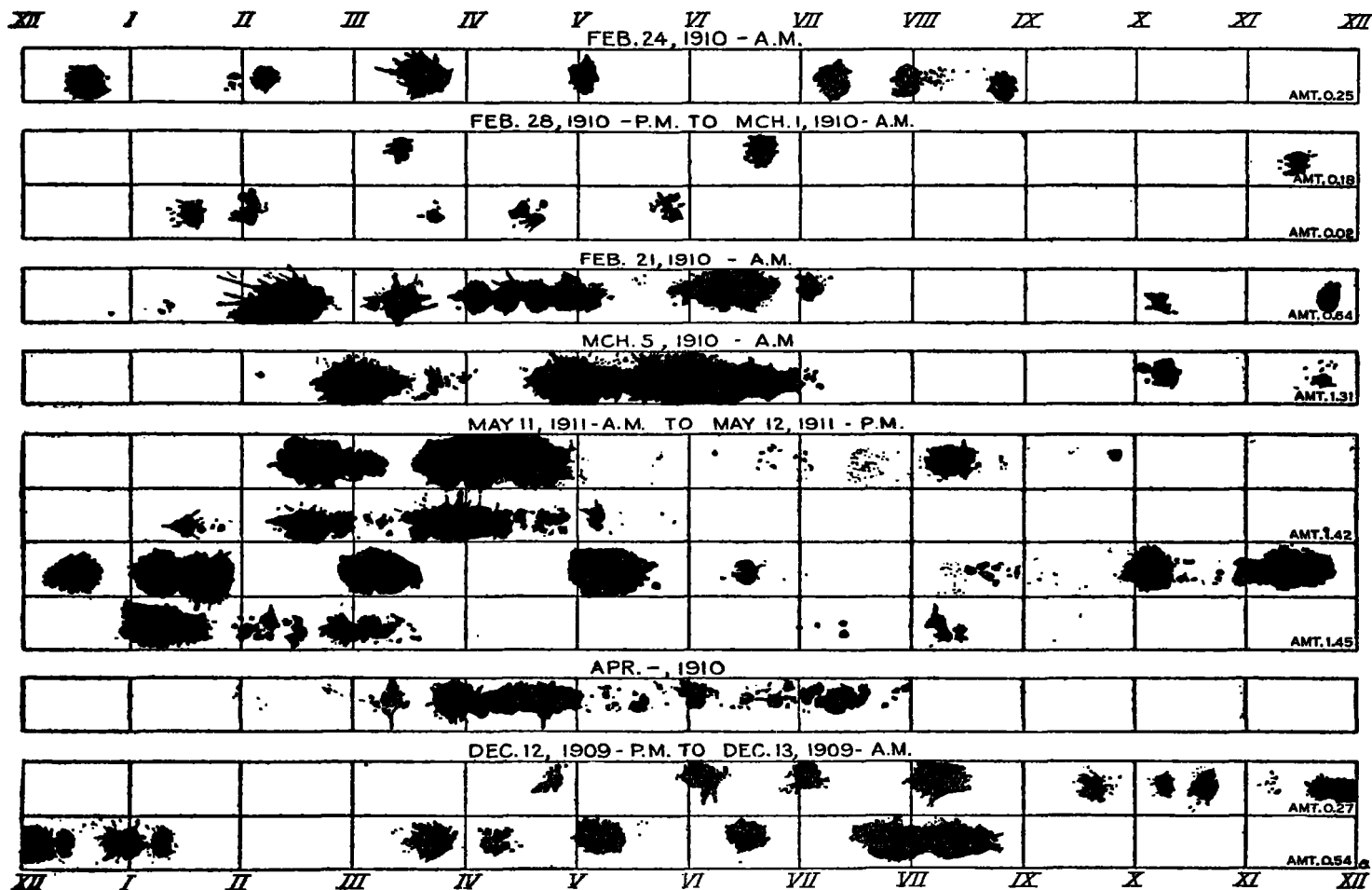
Duration.	Depths of precipitation.	Duration.	Depths of precipitation.
Minutes.	Inches.	Minutes.	Inches.
5	0.25	35	0.55
10	0.30	40	0.60
15	0.35	45	0.65
20	0.40	50	0.70
25	0.45	60	0.80
30	0.50		

<sup>1</sup> Precipitation will be considered excessive when it equals or exceeds 2.5 inches (63.5 mm.) in 24 consecutive hours, or 1 inch in 1 hour. . . .



A. Baltimore, Md.

(Hourly amounts in hundredths of an inch given by small figures within the hour spaces, XII=noon.)



B. San Juan, P. R.

(Subdivisions represent hour intervals, 12-hour totals in inches at the right.)

FIG. 2.—“Rain autographs” or automatic records showing duration and intensity of rainfall at Baltimore, Md. (A), and at San Juan, P. R. (B).

TABLE 3.—*Greatest duration of excessive rains (in minutes).*

	Jan.	Feb.	Mar.	Apr.	May.	June.	July.	Aug.	Sept.	Oct.	Nov.	Dec.	Year.	Cases.
San Juan, P. R. (12 years).....	95	20	75	110	170	39	80	140	102	68	81	95	170	193
Baltimore, Md. (10 years).....	22	.....	6	.....	37	30	80	50	45	61	.....	.....	80	78

## B. FREQUENCY OF RAINS.

Rainfall frequency is so largely a matter of local topography that it is a difficult matter to make a comparison which will fairly represent the difference between the tropics and the middle latitudes in this respect. The average monthly and annual number of days with rain for the entire island of Porto Rico is compared with that of the entire State of Maryland. In both cases the numbers represent the average of about 40 stations for a period of 15 to 20 years.

The value of such a comparison is of course largely dependent upon the representative character of the region selected. Both regions show a fairly even distribution of rainy days through the year. The greater frequency of rains in the tropical region is to be expected, owing to a higher mean temperature and humidity (Tables 4 and 5, and fig. 3).

TABLE 4.—*Total frequency of rains.*

	Jan.	Feb.	Mar.	Apr.	May.	June.	July.	Aug.	Sept.	Oct.	Nov.	Dec.	Year.
San Juan (10 years).....	20	14	17	17	17	17	19	20	18	17	19	21	213
Porto Rico (16 years), 40 stations.....	14	10	12	11	14	14	15	15	16	16	15	14	166
Baltimore (44 years).....	12	11	13	11	11	11	11	11	9	9	9	11	129
Maryland (20 years), 40 stations.....	10	8	10	9	9	10	10	10	7	7	7	8	105

TABLE 5.—*Frequency of stated amounts of rainfall.*

	0.01 to 0.10 inch.	0.11 to 0.25 inch.	0.26 to 0.50 inch.	0.51 to 1.00 inch.	Over 1 inch.	Total annual frequency.	Total number of rains.
Annual frequency:							
San Juan, P. R. ....	96	43	34	21	15	209	2,300
Baltimore, Md. ....	56	25	22	18	10	131	4,300
Percentage of frequency:	P. ct.	P. ct.	P. ct.	P. ct.	P. ct.		
San Juan, P. R. ....	46	21	16	10	7	209	2,300
Baltimore, Md. ....	43	19	17	14	8	131	4,300

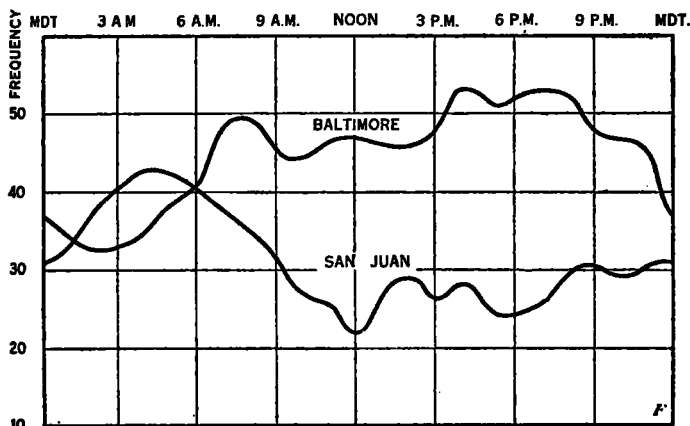


FIG. 3.—Hourly rainfall frequency per annum at Baltimore, Md., and at San Juan, P. R.

## Frequency of excessive rains.

In comparing the frequency of *excessive* rains we find a much greater difference. For example, during a 12-year period (1899–1911) at San Juan there were 193 excessive rains as compared with 78 at Baltimore during a period of 10 years. Allowing for the difference of two years in the periods, the frequency at San Juan is more than double that at Baltimore.

The distribution through the year is more uniform in the Tropics than in the middle latitudes; in the latter zone the excessive rains are confined almost entirely to the summer months. The influence of the hurricane season is clearly shown in the figures for July to November in the Tropics (Table 6).

TABLE 6.—*Average frequency of excessive rains.*

	Jan.	Feb.	Mar.	Apr.	May.	June.	July.	Aug.	Sept.	Oct.	Nov.	Dec.	Year.
San Juan (12 years).....	12	1	6	11	16	19	24	27	25	20	20	12	193
Baltimore, Md. (10 years)...	1	0	1	0	13	13	18	20	8	3	.....	.....	78

## Frequency of stated amounts of rainfall.

A matter of very great moment in agricultural pursuits, the importance of which is generally overlooked, is the frequency of stated amounts of rainfall and their distribution through the year. Frequent moderate rains are generally more favorable for plant growth than heavier rains, assuming equal total amounts for the year. There is a wide range in the frequency of rains of 0.01 to 0.10 inch in Porto Rico, a condition which is probably common to all regions with pronounced differences in topography. As the amounts grow larger the range rapidly decreases (fig. 4).

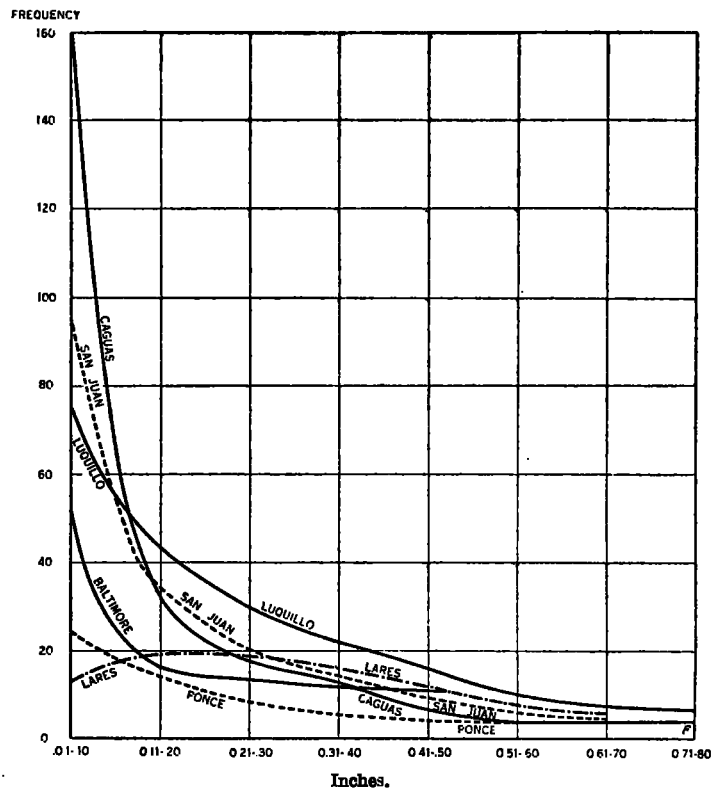


FIG. 4.—Frequency per annum of stated amounts of rainfall at selected localities in Porto Rico and at Baltimore, Md.

The best and most extensive tobacco plantations of Porto Rico are situated in the portion of the island having the greatest number of light rains, with a total annual amount close to the average for the entire island. The station at Caguas, typical of this region, shows a record of 160 days with rainfall from 0.01 to 0.10 inch, with a total annual frequency of 262 days and a total rainfall of 68 inches.

In the mountains of the western portion of the island, a region noted for the abundance and fine quality of its coffee, the rainfall is very heavy. A peculiarity of the rains of this region is that they show a maximum frequency of amounts between 0.20 and 0.30 inch, whereas the usual record shows a very decided preponderance of amounts less than 0.10 inch.

### C. INTENSITY OF RAINFALL.

A comparison of excessive rates of rainfall at San Juan and at Baltimore reveals some interesting facts. The heaviest half-hour rainfall at Baltimore, during a period of 15 years, shows a greater intensity than the heaviest half-hour fall at San Juan during a similar period. However the Baltimore rainfall in question continued excessive but little more than 40 minutes, while at San Juan the rate was excessive for 1 hour and 40 minutes.

Still more surprising are the curves of figure 7, showing the average values for all excessive rains at Baltimore and at San Juan for a period of 10 years. The curves are identical for the first 15 minutes after which the San Juan curve drops below the Baltimore curve and continues well below to the end of the excessive rate of fall. Again the San Juan rains show a longer period of excessive rates, averaging 1 hour and 20 minutes for Baltimore and 2 hours for San Juan.

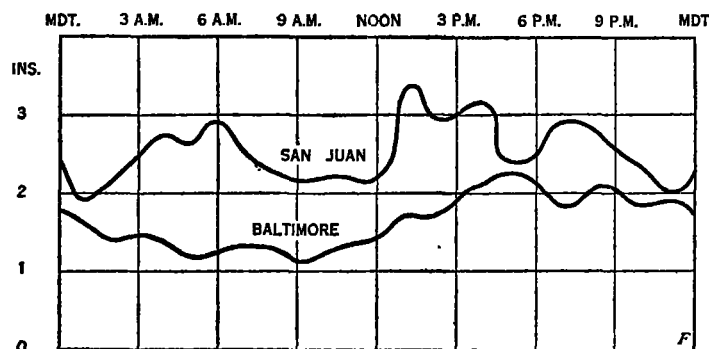


FIG. 5.—Curves of average hourly rainfall, per annum, at Baltimore, Md., and San Juan, P. R.

TABLE 7.—Average hourly amounts of rainfall per year at San Juan, P. R., and at Baltimore, Md. (Inches.)

	Hour ending—A. M.												P. M.											
	1	2	3	4	5	6	7	8	9	10	11	Noon.	1	2	3	4	5	6	7	8	9	10	11	Mdt.
San Juan.....	0.70	0.68	0.70	0.75	0.72	0.84	0.71	0.80	0.73	0.94	1.04	1.18	1.56	1.19	1.32	1.32	1.28	1.44	1.45	1.26	0.99	0.95	0.77	0.89
Baltimore.....	1.87	2.17	2.33	2.72	2.56	2.93	2.51	2.32	2.13	2.18	2.20	2.10	3.44	2.96	3.01	3.15	2.39	2.47	2.93	2.85	2.59	2.41	1.98	2.36

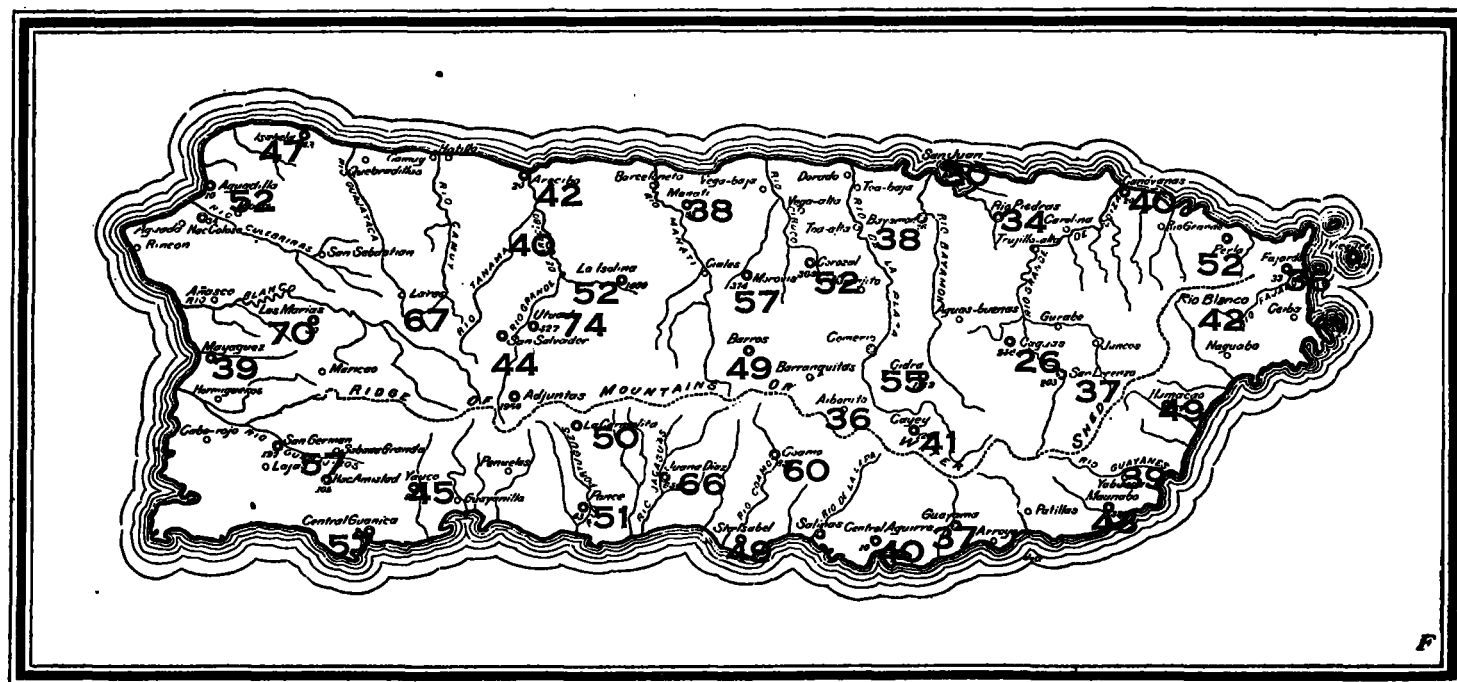


FIG. 6.—Average rainfalls (hundredths of an inch) on days with rain in Porto Rico. (Small italic figures give altitude in feet.)

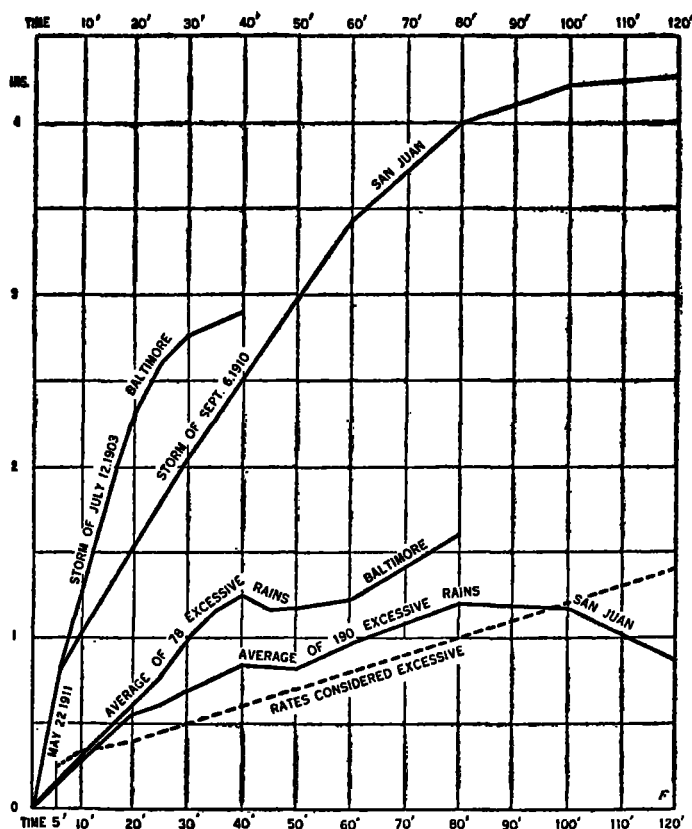


FIG. 7.—Various excessive rainfalls at Baltimore, Md., and at San Juan, P. R. Dotted line indicates rates at present called "excessive" by the U. S. Weather Bureau.

TABLE 8.—Average rainfall on days with rain, San Juan, P. R., and Baltimore, Md. (Inches.)

	Jan.	Feb.	Mar.	Apr.	May.	June.	July.	Aug.	Sept.	Oct.	Nov.	Dec.	Year.
San Juan.....	0.23	0.15	0.20	0.29	0.32	0.35	0.32	0.38	0.37	0.35	0.40	0.30	0.31
Baltimore.....	0.26	0.32	0.31	0.29	0.30	0.37	0.41	0.39	0.41	0.30	0.30	0.29	0.32

TABLE 9.—Greatest intensity of rainfall at San Juan, P. R., and at Baltimore, Md.

	Minutes.					
	5	10	15	30	60	120
Greatest precipitation in:	Inches.	Inches.	Inches.	Inches.	Inches.	Inches.
San Juan, P. R.....	0.79	1.02	1.31	2.09	3.43	4.21
Baltimore, Md.....	0.80	1.35	1.92	2.75	2.87	2.87
Rates per hour:						
San Juan.....	9.48	6.12	5.24	4.18	3.43	4.21
Baltimore.....	9.60	8.10	7.68	5.50	2.87	1.44

TABLE 10.—Weight of rainfall.  
[A—Storm of Sept. 6, 1910, at San Juan, P. R. B—Storm of July 12, 1903, at Baltimore, Md.]

Duration.	Depth.		Tons per acre.	
	A San Juan.	B Baltimore.	A San Juan.	B Baltimore.
	Inches.	Inches.		
First 5 minutes.....	0.08	0.33	9	37
First 10 minutes.....	0.25	0.98	28	111
First 15 minutes.....	0.40	1.72	45	195
First 30 minutes.....	0.95	2.69	107	304
First 45 minutes.....	1.71	.....	194	.....
First 60 minutes.....	2.61	.....	295	.....
First 80 minutes.....	3.96	.....	450	.....

### The seasonal distribution of rainfall in Porto Rico.

Accompanying charts (figs. 14 and 15) show the normal annual distribution over the island and the distribution during a dry year (1907) and during a wet year (1901). The striking features of the geographical distribution are the comparatively light rainfall on the south side and the comparatively heavy rainfall through the center of the island. This distribution is readily accounted for by the topography of the island (figs. 12 to 15).

The rainfall of November, 1901, shown in the accompanying map, represents the geographical distribution of rain during a month of frequent heavy rains associated with the passage across the North Atlantic of several well-developed cyclonic and anticyclonic areas, and points to one of the most prolific causes of heavy rains in Porto Rico, next to the passage of hurricanes (fig. 8).

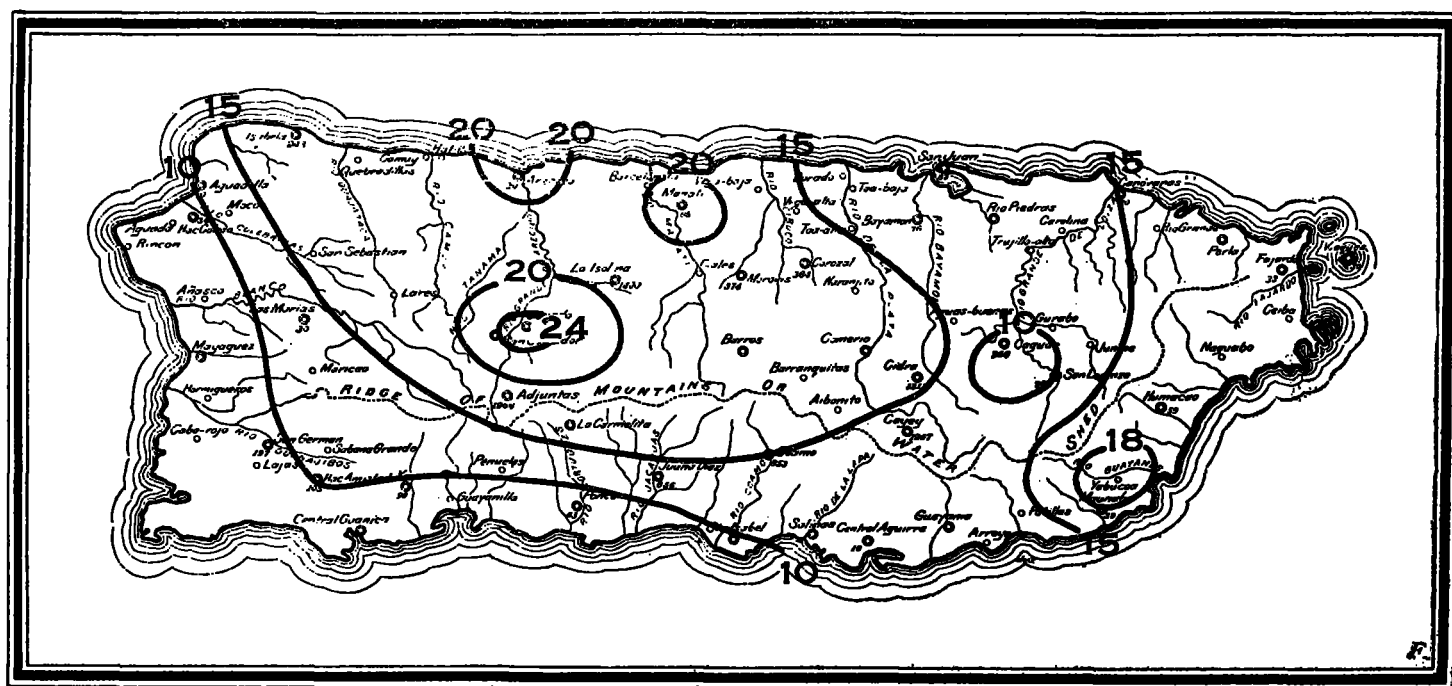


FIG. 8.—Porto Rico rainfall (inches) for November, 1909. [A wet, stormy month. A succession of pronounced highs and lows crossed the North Atlantic, extending their influence into the Tropics.] (Small italic figures give altitudes in feet.)

*Hurricanes and rainfall in Porto Rico.*

The heaviest general rains of the island are associated with the passage of hurricanes in the comparatively rare instances in which the center of a tropical cyclone or a secondary development therefrom passes over or very close to the region in question. The only exceptionally severe storm of this character in recent years, one which devastated the island to an unusual extent, occurred on August 8, 1899. It is one of the historic storms of the West Indies. The center of this storm passed directly across the center of Porto Rico from east to west, and the rainfall was accurately measured by trained observers all along the path of the storm.

A cross section of the storm as it passed over San Juan was shown in a diagram<sup>2</sup> by means of hourly observations of all the principal weather conditions. The rainfall distribution and progressive movement of the storm across the island are shown in figure 11. The entire path of the storm, from its inception east of the Windward Islands to the Florida coast, thence northeastward along the Atlantic coast to the banks of Newfoundland was shown in the chart forming Plate XVIII of Weather Bureau Bulletin X.

The weight of water precipitated upon the island of Porto Rico in the 30 hours during which the storm prevailed has been computed. Basing the calculations an average fall of 10 inches over the entire island, the total weight of the rainfall was approximately 2,602,920,000 tons, equivalent to 723,200 tons per square mile or 1,113 tons per acre.

<sup>2</sup> See Hurricanes of the West Indies, by O. L. Fassig. Washington, 1913 (W. B. Bull. X) Plate XVI.

TABLE 11.—Weight of rainfall during hurricane of August 8, 1899.

Average rainfall over entire island (30 hours).....inches..	10
Area of island.....square miles..	3,600
Weight of a sheet of water 10 inches deep, tons per acre.....	1,130
Do.....tons per square mile..	723,200
Do.....tons, whole island..	2,602,920,000
Depth of rainfall over center of island (25 square miles), inches.....	23
Weight of 23 inches of water.....tons per square mile..	1,663,360
Do.....tons over 25 square miles..	41,584,000

TABLE 12.—Summary of rainfall data, Island of Porto Rico.

Year.	Total annual rainfall.	Greatest local annual rainfall.	Least local annual rainfall.	Greatest rainfall in 24 hours.	Number of days with rain.
	Inches.	Inches.	Inches.	Inches.	Days.
1899.....	80.40	140.06	50.62	23.00	182
1900.....	77.52	151.92	39.89	12.23	172
1901.....	93.82	168.96	38.51	17.02	176
1902.....	82.65	141.17	46.08	9.06	165
1903.....	69.09	115.08	21.42	6.40	152
1904.....	75.13	131.01	36.00	6.00	159
1905.....	72.08	122.13	30.12	8.05	174
1906.....	68.39	107.03	26.86	8.48	159
1907.....	63.54	99.58	20.60	7.10	171
1908.....	66.96	107.11	29.70	5.38	172
1909.....	79.65	127.45	51.02	12.90	167
1910.....	66.83	107.64	23.98	18.22	161
1911.....	72.58	109.31	28.77	10.30	174
1912.....	69.25	121.73	35.83	10.72	160
1913.....	64.71	99.00	23.43	6.50	171
1914.....	67.74	138.50	18.83	10.70	161
Means.....	73.15	129.58	32.60	10.75	167

TABLE 13.—Summary of rainfall data for entire island of Porto Rico (1899–1914).

	Jan.	Feb.	Mar.	Apr.	May.	June.	July.	Aug.	Sept.	Oct.	Nov.	Dec.	Annual.
Average rainfall (inches).....	3.63	2.52	3.87	4.94	7.43	6.88	6.32	7.77	8.09	8.80	7.70	5.05	73.05
Greatest monthly rainfall (inches).....	7.23	4.25	8.03	7.71	13.55	16.07	12.15	15.72	11.55	14.61	13.67	9.49	93.82
Least monthly rainfall (inches).....	1.57	0.47	1.57	1.22	4.11	2.55	4.39	4.98	4.99	5.27	3.87	1.67	63.54
Greatest rainfall in 24 hours (inches).....	8.10	4.55	9.32	12.23	10.70	9.06	17.02	23.00	18.22	10.72	12.90	10.55	23.00
Greatest local monthly rainfall (inches).....	35.64	22.64	18.45	26.21	32.89	33.30	33.58	32.22	29.24	28.41	26.52	22.62	168.96
Least local monthly rainfall (inches).....	0	0	0	0	0	0	0	0.32	0.20	0.87	0.45	0	18.83
Average number of days with rain.....	14	10	12	11	14	14	15	15	16	16	15	14	167
Greatest number of days with rain.....	17	14	18	14	20	20	20	19	18	20	19	21	182
Least number of days with rain.....	9	3	7	6	10	9	11	13	14	13	9	8	152
Mean departure from normal rainfall.....	1.8	1.4	2.0	2.2	2.3	3.8	2.4	3.3	2.3	2.8	3.4	2.5	10.8

JAN. FEB. MCH. APR. MAY JUNE JULY AUG. SEP. OCT. NOV. DEC. JAN.

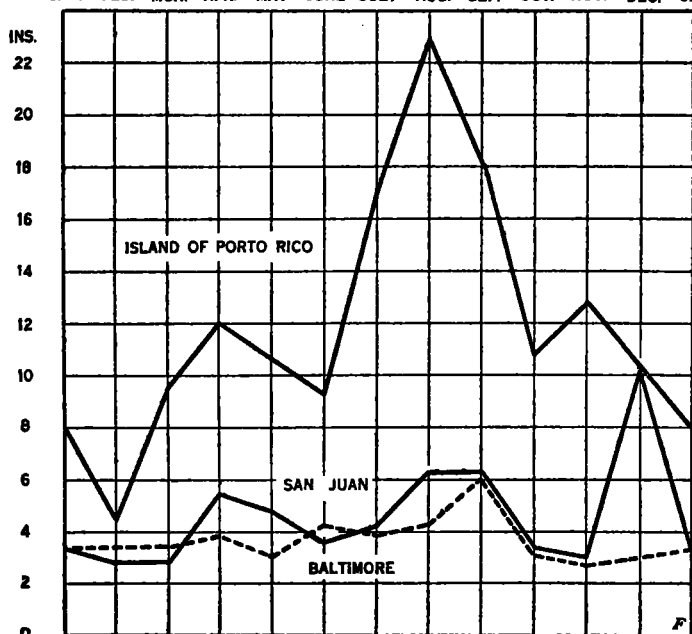


FIG. 9.—Maximum 24-hour falls for Porto Rico, San Juan, P. R., and Baltimore, Md.

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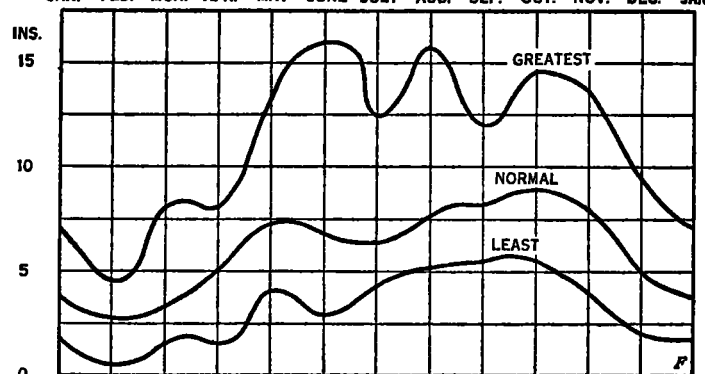


FIG. 10.—Monthly rainfalls for Porto Rico, 1899–1914.

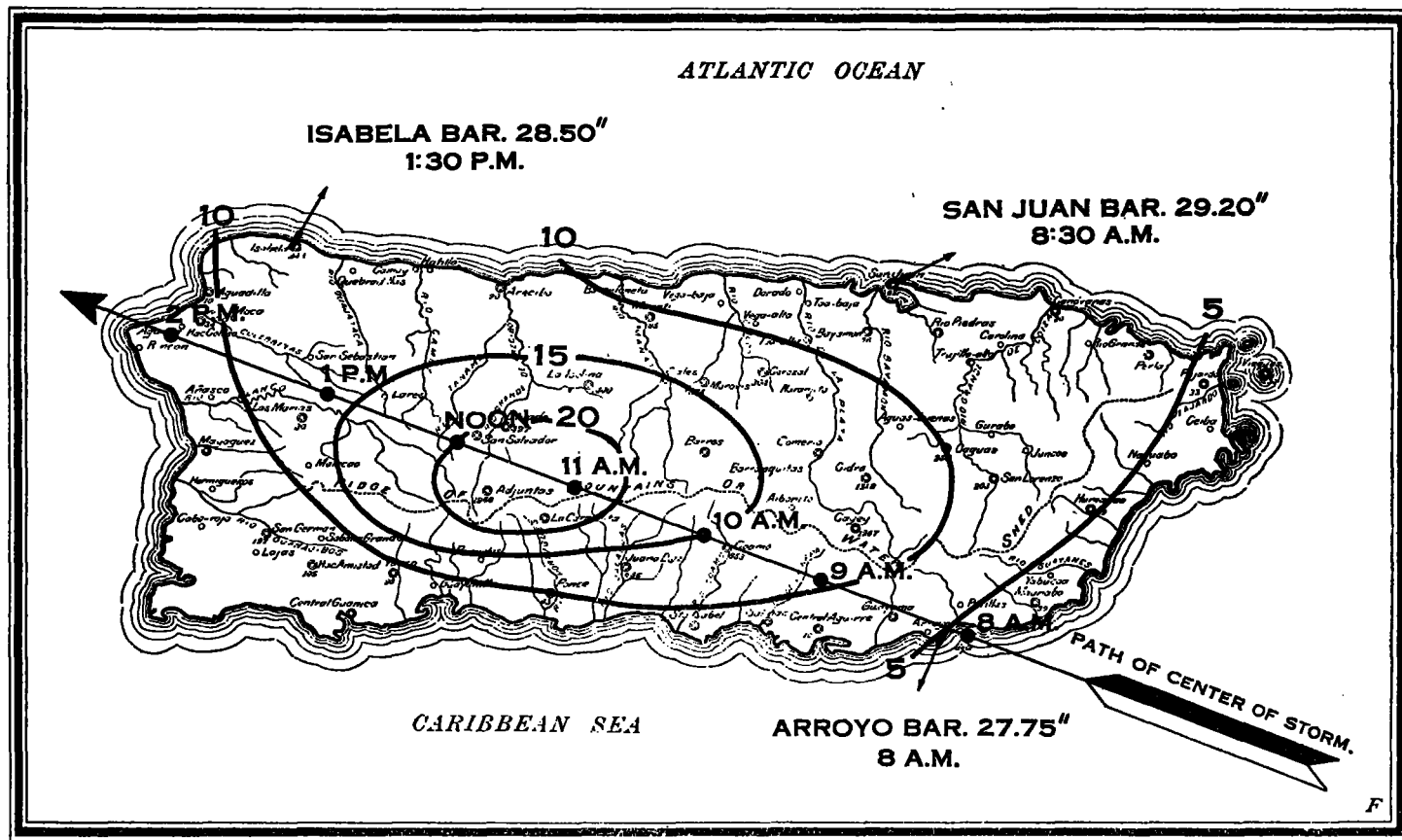


Fig. 11.—Rainfall over Porto Rico during the passage of the hurricane of Aug. 5-9, 1899. Successive positions of the center of the storm are indicated by the dots on the arrow showing its path which is about 80 miles across the island. The maximum 24-hour rainfall was 23 inches, recorded at Adjuntas.

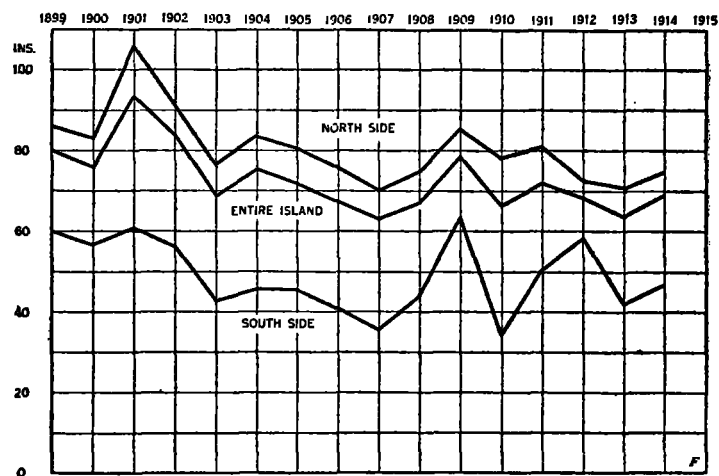


Fig. 12.—Average annual rainfalls for the two sides and the whole of the island of Porto Rico, 1899-1914.

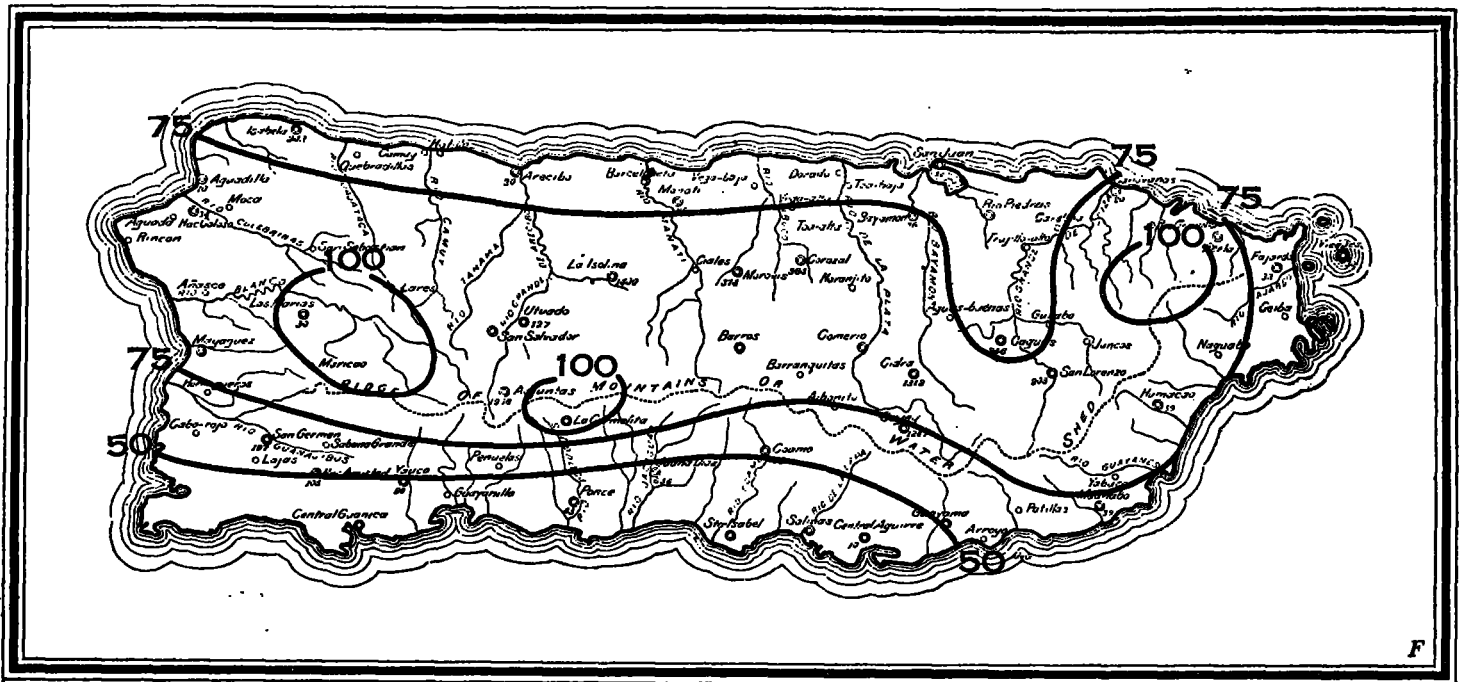


FIG. 13.—Distribution of the normal annual rainfall of Porto Rico. (Rainfall in inches; small italic figures give altitudes in feet.)

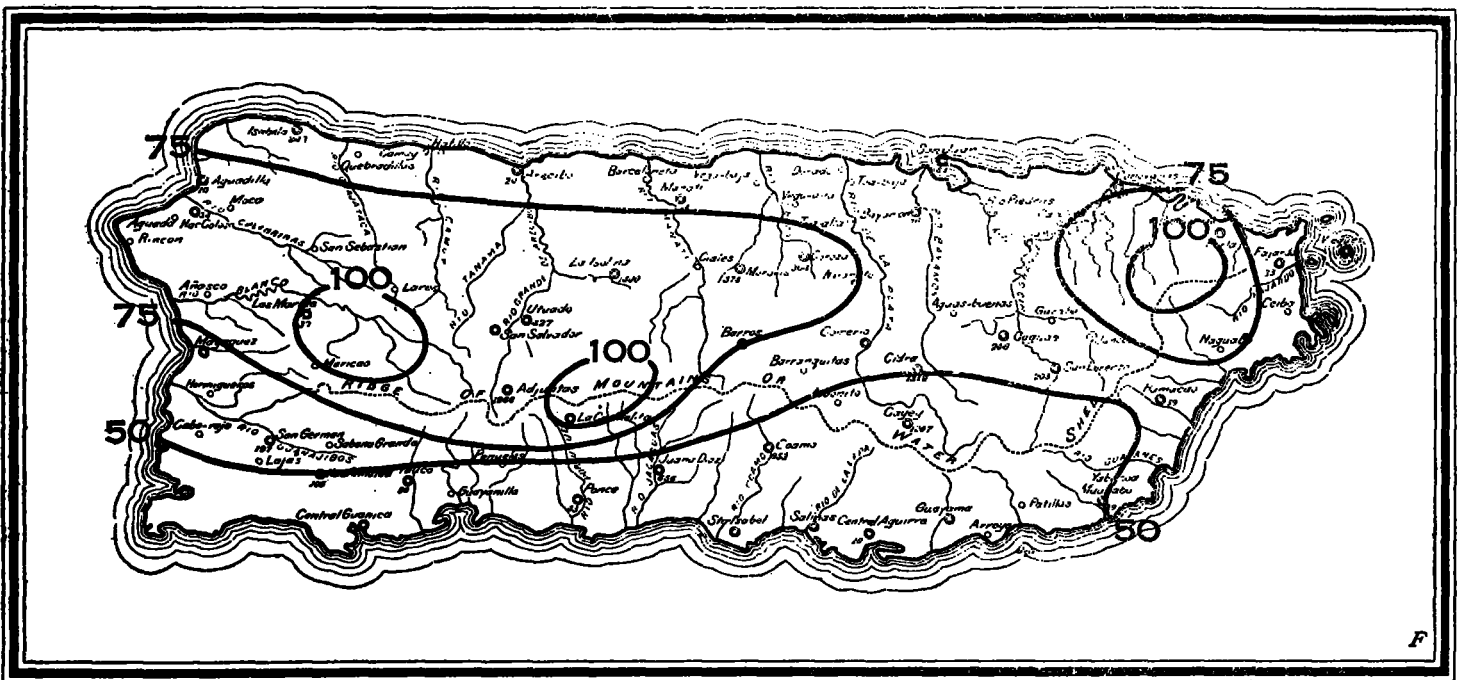


FIG. 14.—Annual rainfall of Porto Rico in a dry year, 1907. (Rainfall in inches; small italic figures give altitudes in feet.)



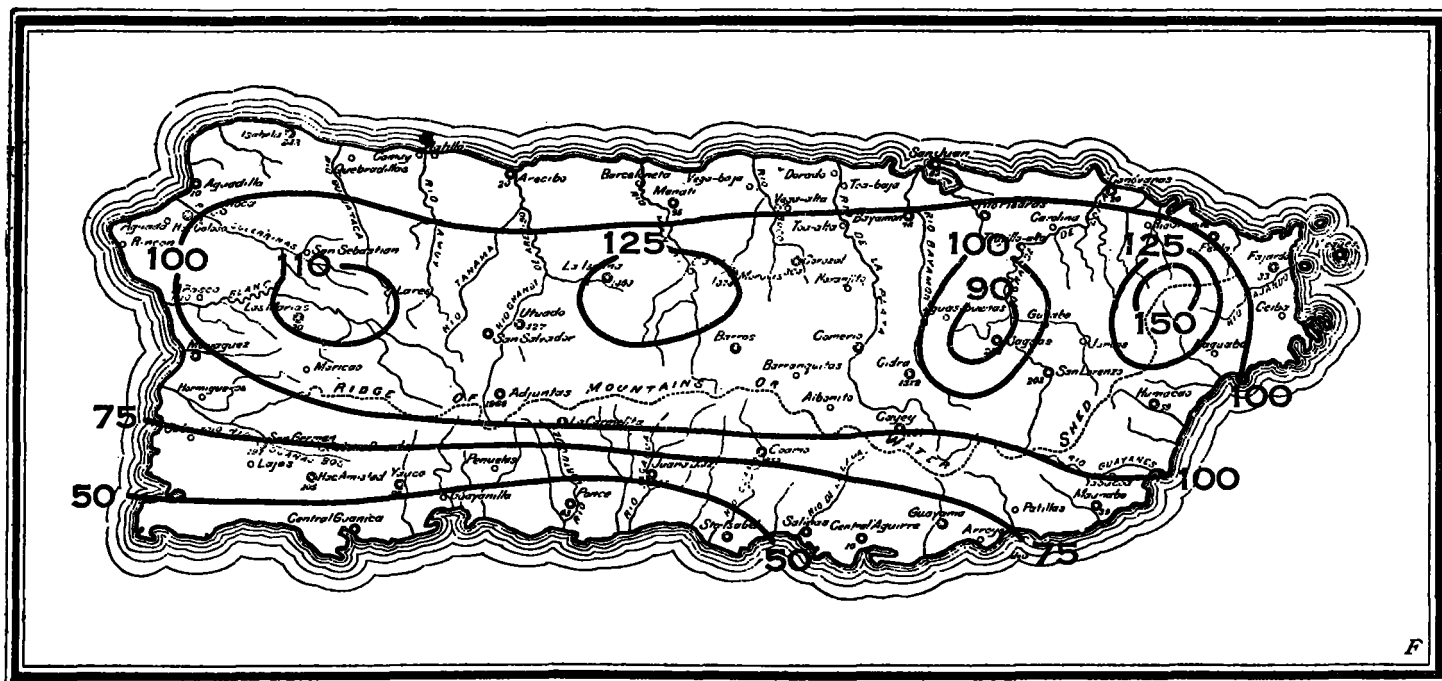


FIG. 15.—Annual rainfall of Porto Rico in a wet year, 1901. (Rainfall in inches; small italic figures give altitudes in feet.)

### THE MECHANISM OF CYCLONES.

By F. J. W. WHIPPLE.

[Abstract reprinted from Report of the 85th Meeting of the British Association for the Advancement of Science, Manchester, 1915. p. 367.]

The distribution of pressure and temperature in cyclones in the Temperate Zone has been learned from the analysis of the records from the meteorographs carried by [sounding] balloons. Up to a height of 8 or 9 kilometers the cyclone is composed of air cooler than its surroundings: at greater heights, i. e., in the stratosphere, the cyclone contains comparatively warm air. The lower limit of the stratosphere is depressed in the cyclone. This temperature distribution indicates that the air constituting the lower part of the cyclone has recently ascended, whereas the upper air has recently fallen, and accordingly the arrival of a cyclone is marked by an outflow of air at the bottom of the stratosphere and an inflow below. At the beginning of the present paper the amount of this displacement of air is estimated on the assumption that there is no direct exchange of heat, and it is shown that the outflow is concentrated between the 7th and 10th kilometers and is about 6.5 times the net loss of air as estimated by the fall of pressure at the earth's surface.

It is pointed out that a cyclone may be regarded as a disturbance in the stream of air which flows from west to east in the Temperate Zone, and the form of the isobars obtained by superimposing the permanent pressure distribution and the temporary cyclonic distribution is discussed. It is shown that when due allowance is made for the curvature and the progressive motion of these isobars, the gradient wind at certain heights is much less than it would have been if the curvature were inappreciable, so that at these heights the air supply from the rear to the front of the cyclone fails and the cyclone appears to move under the influence of suction applied at the base of the stratosphere. The explanation may be summarized as follows:

If the flow of air at any level were entirely horizontal and along the isobars, and if the changes of density were

negligible, then the condition for continuity would require the velocity to be inversely proportional to the distance between the isobars, i. e., the velocity would be directly proportional to the pressure gradient. This condition is not satisfied, however, in regions where the air trajectories are curved. The pressure has to produce the centripetal acceleration in the curved path in addition to overcoming the tendency to turn to the right, which is the feature of all horizontal motion in our hemisphere. Accordingly the actual velocity where the isobars are curved is less than it should be to secure continuity and maintain a stationary distribution of pressure. The effect of curvature in reducing the velocity is greatest at the heights where the winds are strongest, and therefore the suction effect is concentrated near the base of the stratosphere.

The general argument is supported by the analysis of two special cases.

### CAUSES CONTRIBUTORY TO THE ANNUAL VARIATION OF LATITUDE.<sup>1</sup>

By HAROLD JEFFREYS.

[Abstract.]

The motion of the terrestrial pole relative to the surface of the earth was shown by Chandler to consist mainly of two parts, viz, a circular motion with a period of 430 days, and an annual motion in an ellipse. The former is considered to be identical with the free vibration called the polhode motion, or Eulerian nutation. The latter is generally attributed to meteorological causes. An elaborate analysis of these causes is published by Mr. H. Jeffreys in the "Monthly Notices." The author examines separately the effects of atmospheric motion, oceanic movements, precipitation, vegetation, and polar ice. He concludes that "the known meteorological causes are apparently capable of giving a fairly good account of the observed annual motion of the pole, the errors found being perhaps within the range of uncertainty of the data."

<sup>1</sup> See Monthly notices, Roy. astron. soc., London, April, 1916, 76: 499-525. Pl. 3.